Chapter 6. SUBSURFACE HYDROLOGY

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6.1 Introduction

Root zone soil water redistribution is an important part of the WEPP model hydrology because 1) soil water content affects the subsequent rainfall/runoff events, 2) root zone soil water content is used in the interaction between soil water and plant growth, and 3) soil water content is used in residue decomposition.

The objective of this chapter is to present subsurface lateral flow and the surface and subsurface drainage routines. The governing equations along with the assumptions and application criteria are discussed. Furthermore, WEPP hydrology was tested on a poorly drained soil with and without an artificial subsurface drainage system. The validation results are presented in this chapter.

6.1.1 Model Sensitivity To Water Table Fluctuation

Sensitivity of WEPP runoff and erosion prediction to fluctuation of the water table on a silt loam soil is shown in Figures 6.1.1 and 6.1.2. The model was run using a hypothetical site with a silt loam soil, and a saturated hydraulic conductivity (k_s) of 13 $mm \cdot h^{-1}$. The rainfall depth assumed was 60 *mm* with a duration of 60 min. The water table depth was the only parameter changed between the runs. The model simulated excess rainfall and soil loss reductions as the water table lowered. Therefore, the results of the WEPP sensitivity analysis complement the quantitative studies of the effects of subsurface drainage on runoff and erosion by Istok and Kiling (1983).

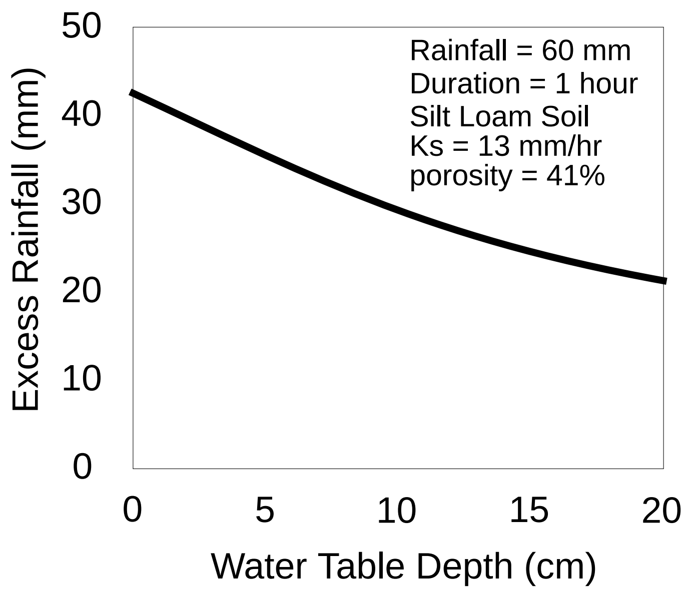

Figure 6.1.1. Sensitivity of the WEPP runoff calculations to water table depth.

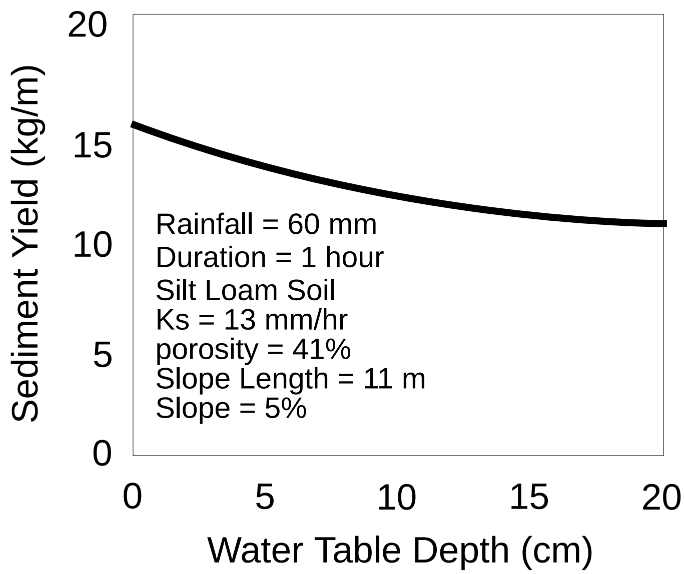

Figure 6.1.2. Sensitivity of the WEPP sediment yield calculations to water table depth.

6.2 Subsurface Hydrology Description

6.2.1 Subsurface Lateral Flow

Hortonian overland flow (Horton, 1933) prevails when the rainfall intensity exceeds soil infiltrability and has been considered the only source of runoff generation in most hydrologic models. However, on hillslopes with a soil surface of high hydraulic conductivity and with a flow-restricted layer at shallow depths, subsurface flow may be the dominant portion of storm water yield (Hursh, 1936). Subsurface stormflow has been reported from a wide variety of regions (Dunne 1978). Field studies of subsurface stormflow have shown that the presence of inhomogeneities in the soil causes subsurface stormflow to be a significant portion of hillslope water yield. Beven (1981) reviewed the field and theoretical studies of subsurface stormflow, and he concluded that these processes may contribute a significant portion of storm water yield if the following conditions prevail: 1 - soils of high permeability, whether inherent in the soil matrix or due to structural or biotic macropores. 2 - A steep hydraulic gradient, whether due to the slope steepness or to the buildup of groundwater mounds on shallow slopes. On unvegetated agricultural lands and in urban areas with soil surfaces of low hydraulic conductivity, simulation of Hortonion type overland flow is appropriate. On the other hand, on steeply-sloping forested watersheds which have significant organic litter and high hydraulic conductivities, simulation of subsurface flow is needed to better estimate storm water yield (Mosely, 1979; and Sloan and Moore, 1984).

Sloan and Moore (1984) evaluated five physically-based subsurface flow models. The model results were compared with measured subsurface flow from a hillslope of uniform slope steepness. Evaluations included one- and two-dimensional finite element models, a Kinematic wave model, and two simple storage-discharge models based on the Kinematic wave and Bovssinesq assumptions (Sloan and Moore, 1984). They concluded that simple, physically-based models adequately simulated the storm subsurface flow response of a steeply-sloping forested watershed (Sloan and Moore 1984). After extensive search on existing methods to simulate subsurface lateral flow, a Kinematics storage - discharge model developed by Sloan and Moore (1984) was selected for use in the WEPP model. The Sloan and Moore (1984) subsurface lateral flow model uses the mass continuity equation with the entire hillslope as control volume (Fig. 6.2.1). Furthermore, it assumes an idealized hillslope segment of length L, slope angle of α, and impervious boundary layer at depth D (Fig. 6.2.1).

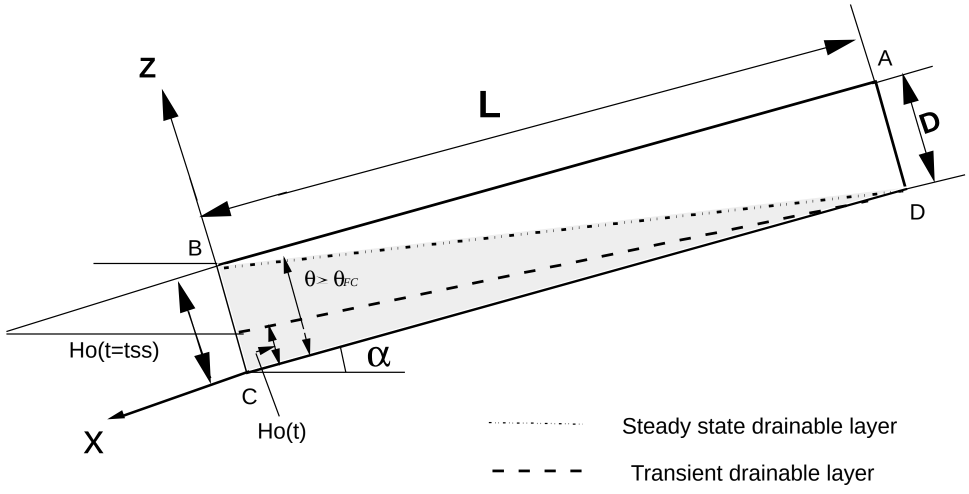

Figure 6.2.1. Schematic representation of the Kinematic storage model (Sloan and Moore, 1984).

In WEPP, we assume that the soil layer with water content in excess of field capacity, θ_{FC} (water held at 33KPa tension for most soils), is subjected to percolation to a lower layer (see chapter 5) and to lateral flow. Such a soil layer is referred to as a drainable layer hereafter. The mass continuity equation in finite difference form for a given hillslope can be written as:

$$\frac{S_2 - S_1}{d_2 - d_1} = Pe - (D + ET)\, L - \frac{q_1 + q_2}{2} \qquad [6.2.1]$$

where S is the drainable depth of water (m), d is the day of simulation, Pe is the percolated water to the drainable layer ($m \cdot d^{-1}$), D is seepage out of the drainable layer ($m \cdot d^{-1}$), ET is actual evapotranspiration from drainable layer ($m \cdot d^{-1}$), L is the length (m) and q is discharge from the hillslope per unit width (m) (Sloan et al, 1983). Since the WEPP water balance simulates daily Pe, D and ET, calculation of subsurface lateral flow is done on a daily basis (see Chapter 5 for more detail). The drainable volume of water is calculated by

$$S = H_o\, \theta_d\, L/2 \qquad [6.2.2]$$

where, H_o is the thickness of drainable layer normal to slope (m), and θ_d is drainable water and is calculated as

$$\theta_d = \theta - (\theta_{FC} - \theta_a) \qquad [6.2.3]$$

where θ is total soil moisture ($m^3 \cdot m^{-3}$), θ_{FC} is soil water content at field capacity ($m^3 \cdot m^{-3}$), and θ_a is entrapped air ($m^3 \cdot m^{-3}$).

Subsurface lateral flow from a hillslope of 1 meter width is calculated using the equation

$$q = 86400\, H_o\, K_{e(\theta)} \sin(\alpha) \qquad [6.2.4]$$

where q is subsurface lateral flow ($m \cdot d^{-1}$), K_e is the horizontal hydraulic conductivity ($m \cdot s^{-1}$) at moisture content θ, and α is the average slope angle (Fig. 6.2.1).

The drainable thickness, H_o (*m*), for any given day is calculated by (Sloan and Moore 1984)

$$H_o(d) = \frac{H_o(d-1)\left[L\ \theta - 86400 K_{e(\theta)} \sin(\alpha) + 2\ L(Pe - (D + ET))\right]}{L\ \theta_d + 86400 K_{e(\theta)} \sin(\alpha)} \qquad [6.2.5]$$

The drainable layer receives water from the upper layer through percolation. The water in the drainable layer is subjected to percolation to lower layer and lateral movement. On the hillside with different overland flow elements (OFEs) (Fig. 6.2.2), the subsurface flow routine simulates the water flow from each OFE to the downslope OFE (Fig. 6.2.2).

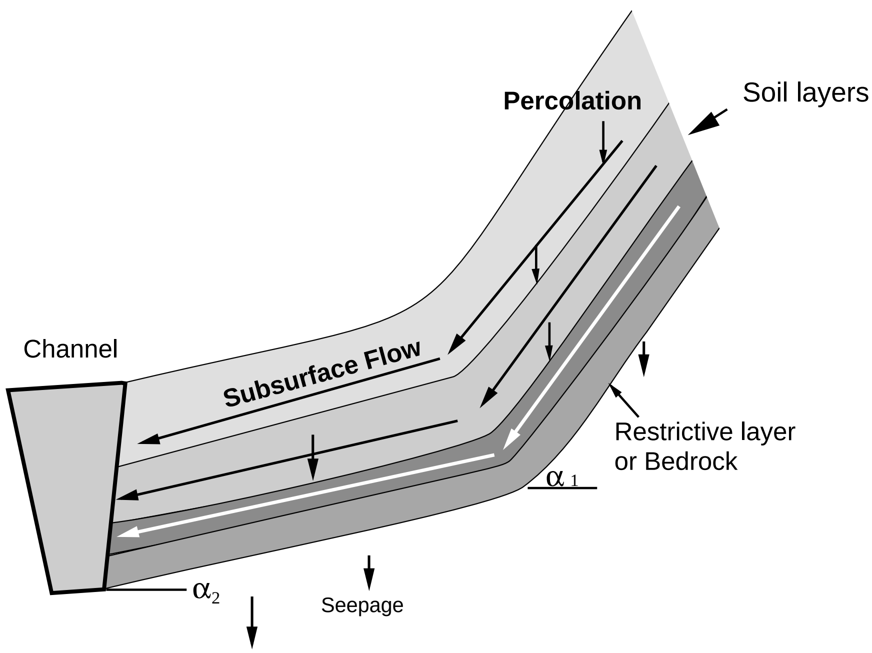

Figure 6.2.2. Percolation and subsurface flow simulation on hillslope with different slope segments.

6.2.2 Surface Drainage

In the WEPP model, surface drainage is characterized by the depressional storage. Depressional storage is directly related to soil surface micro-relief features and generally enhanced by various soil mechanical practices, such as tillage. Several studies were undertaken to develop methods for quantifying depressional storage, (*DS*), from microrelief data (Mitchell and Jones, 1976; Moore and Larson, 1979; and Onstad, 1984). The method developed by Onstad (1984) is used in WEPP. Maximum depth of depressional storage (*cm*) is calculated using the following equation:

$$DS = 0.112\ R_r + 0.031\ R_r^2 - 0.012\ R_r\ S_p \qquad [6.2.6]$$

where R_r is random roughness (*cm*), and S_p is average slope steepness (%).

Moore and Larson (1979), and Onstad (1984) reported that runoff from a hillslope begins before maximum storage, *DS*, is attained. The rainfall excess required to completely satisfy the hillslope depressional storage, *PR*, is calculated using the equation:

$$PR = 0.329\ R_r + 0.073\ R_r^2 - 0.018\ R_r\ S \qquad [6.2.7]$$

The amount of runoff leaving the hillslope, while depressional storage is filling, is determined using the equation:

$$Q_i = \frac{DS}{PR}\ V_i \qquad FL < DS \qquad [6.2.8]$$

$$Q_i = V_i \qquad FL \geq DS$$

where Q is the runoff rate leaving the profile ($cm \cdot h^{-1}$), V is the excess rainfall rate ($cm \cdot h^{-1}$), i is the interval of rainfall intensity distribution, and FL is the accumulated amount of excess rainfall filling the depressional storage (cm).

The volume of water (V_{wat}) filling the depression storage for each rainfall event can be obtained by subtracting Q from V.

$$FL = \sum_{i=1}^{n} (Q_i - V_i) \qquad FL < DS \qquad [6.2.9]$$

6.2.3 Subsurface Drainage

During the rainy season, water tables on poorly drained soils in humid areas are usually close to the soil surface, thereby causing less infiltration and enhancing runoff and soil loss. Skaggs (1982) reported that improvement in subsurface drainage decreases excess surface water and erosion. Bottcher et al. (1981) reported that a complete subsurface drainage system significantly reduced runoff and sediment losses on a 17 ha field. Istok and Killing (1983) studied the effect of subsurface drainage on runoff and sediment yield from an agricultural watershed in western Oregon. They reported that runoff and sediment yield was reduced about 65% and 55%, respectively, due to installation of a drainage system. They concluded that subsurface drainage can be an effective management practice for erosion control in western Oregon.

Although several drainage simulation models are available (Dierickx et al., 1978; Skaggs, 1978), these models are water balance models and do not predict water-induced erosion. In WEPP, however, the surface and subsurface hydrology are linked with the soil erosion process. Therefore, the effect of water table fluctuations on runoff and erosion is simulated.

The algorithm for simulation of subsurface flow to artificial drain tubes or ditches in WEPP draws heavily from DRAINMOD (Skaggs, 1978). The subsurface flux into drain tubes or ditches depends on the soil hydraulic conductivity, drain spacing and depth, soil depth and water table elevation. Assuming flow in the saturated zone only (Figure 6.2.3), drainage flux in any simulation day is calculated using the equation:

$$Q_{dd} = \frac{8\ K_{zy}\ h_e\ M_d + 4\ K_{zy}\ M_d^2}{L_d^2} \qquad [6.2.10]$$

where Q_{dd} is the drainage flux per unit width ($cm{\cdot}d^{-1}$), K_{zy} is the effective hydraulic conductivity for subsurface drainage ($cm{\cdot}d^{-1}$), M_d is the midpoint water table height (cm), L_d is the distance between drains (cm), d is the day of simulation, and h_e is the equivalent depth (cm), calculated with the Moody (1967) equations:

$$h_e = \frac{h}{1 + \frac{h}{L_d}\left(\frac{8}{\pi}\ln\frac{h}{r} - 3.4\right)} \qquad \frac{h}{L_d} < 0.3 \qquad [6.2.11]$$

$$h_e = \frac{L_d \pi}{8\,(ln(\frac{L_d}{2})) - 1.15} \qquad \frac{h}{L_d} \geq 0.3$$

where h is the distance between the restrictive layer and the drain tube or bottom of the drain ditch, (cm), and r is the drain tube radius (cm).

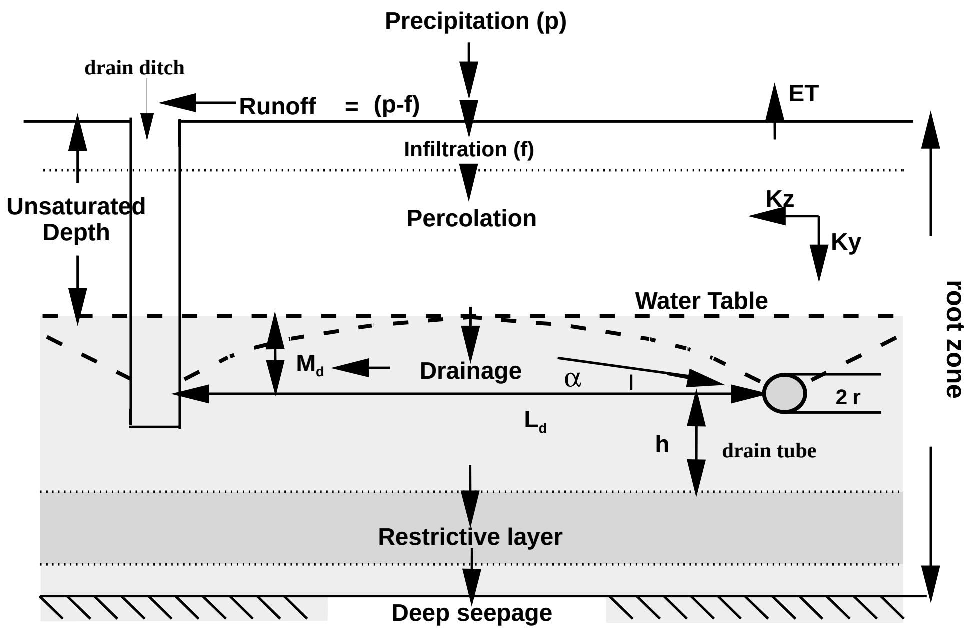

Figure 6.2.3. Schematic representation of WEPP water balance, including artificial subsurface flow.

The equivalent depth, h_e, is used in Equation 6.2.5 to correct for flow convergence near the drain tiles. For the case of flow into the drain ditch, h_e is replaced by h (Fig. 6.2.1).

Effective hydraulic conductivity, K_{zy}, for the direction of drain flow in anisotropic media is calculated using the following equations:

$$\frac{1}{K_{zy}} = \frac{\cos^2(\alpha)}{K_z} + \frac{\sin^2(\alpha)}{K_y} \qquad [6.2.12]$$

$$\tan(\alpha) = \frac{M}{(L_d/2)} \qquad [6.2.13]$$

where K_z = horizontal saturated hydraulic conductivity in saturated zone, ($cm \cdot d^{-1}$), K_y = vertical saturated hydraulic conductivity in saturated zone, ($cm \cdot d^{-1}$), and α = angle of flow path.

Direction of flow is assumed horizontal ($\alpha = 0$) for the case of ditch drainage (Figure 6.3).

The drainage flux calculated with Equation 6.2.10 is limited by the hydraulic capacity of the drain tubes or ditches. The hydraulic capacity of the drain tubes, also called the drainage coefficient (*D.C.*), may be obtained from USDA-SCS-NEH-16 (1971) or by using the Manning equation. When calculated drainage flux is more than *D.C.*, the drainage flux is set to *D.C.*. More detail is given by Skaggs (1978).

Percolation of water from unsaturated layers into the saturated zone raises the water table. Within a saturated zone, soil water is subject to percolation to lower layers, evapotranspiration, and subsurface flow to drain tiles or ditches. Water table draw due to subsurface drainage is calculated as:

$$m_d = m_{d-1} - \frac{Q_{dd}}{\phi_{di}\Delta t} \qquad [6.2.14]$$

$$\phi_{di} = \phi_i - (\theta_{FCi} - \theta_{ai}) \qquad [6.2.15]$$

where d is the day of simulation (d), ϕ_d is the drainable porosity, ($cm^3 \cdot cm^{-3}$), ϕ is the soil porosity ($cm^3 \cdot cm^{-3}$), θ_{FC} is volumetric water content at field capacity ($cm^3 \cdot cm^{-3}$), θ_a is entrapped air volume ($cm^3 \cdot cm^{-3}$), Δt is time-step (1 day), and i is the uppermost soil layer in the saturated zone.

The volume of entrapped air is calculated using soil physical properties such as percent sand, clay, and soil cation exchange capacity (see chapter 5).

Water flowing to the drains (ditch or tile) is assumed to be drawn from the upper saturated layer until the water content approaches drainable porosity. Thereafter, the water will be drawn from the second layer in the saturated zone, and so on. The process continues until the water table is drawn below the tiles or ditch bottoms. At that time water flow to the tiles or ditches is considered negligible and soil water content in each layer is subjected only to percolation and evapotranspiration (soil evaporation and water uptake by plant roots).

6.3 Model Validation

Hydrometeorological records along with soil, vegetation, and topographic data from a poorly drained watershed were used to evaluate the WEPP hydrology component for pre- and post- subsurface drainage installation.

6.3.1 Watershed Description

The watershed (1.4 ha) is located on the hilly western margins of the Williamette Valley, Oregon (Figure 6.3.1), and was fall-planted with winter wheat. The average annual precipitation is 102 cm with about 70% of the total occurring from November through March.

The principal soil series on the study area is Willakenzie silt loam, a member of the fine-silty mixed mesic Ultic Haploxerolfs. These soils consist of a moderately deep silty material overlaying either a palesol or weathered tuffaceous sandstone.

Rainfall was measured on the watershed using a tipping-bucket rain gauge. Watershed runoff measurements were made using H-flumes, bubble gauge and servomanometer water-level sensors. Wells were installed in a transect on each watershed to monitor water tables fluctuations.

A subsurface drainage system was installed on the watershed in August 1979. The drainage system consisted of plastic drain tubing (10 cm in diameter) installed at a depth of .9-1.2 m and a spacing of 12 m (Fig. 6.3.1).

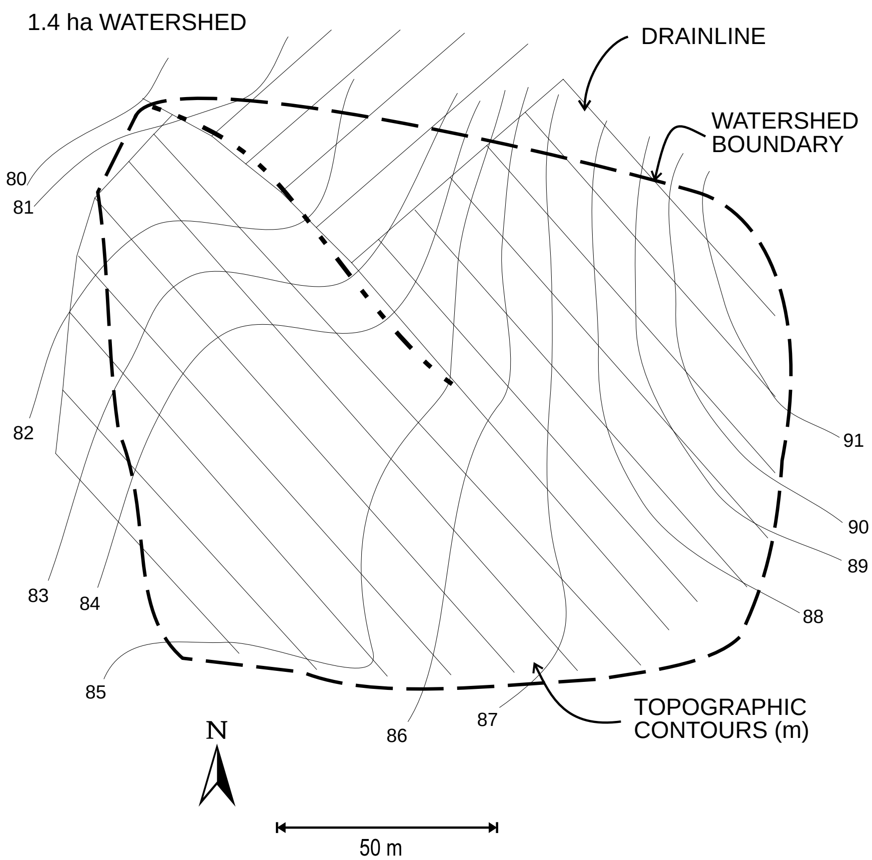

Figure 6.3.1. Map of watershed used in validation, showing boundary, topographic contours and tile drains.

6.3.2 Model Parameters

A brief description of WEPP input parameters is given here; the reader may refer to the User's Summary for more details. The WEPP computer model requires four input data files: climate, soil, slope, and management files. Climate input files include daily maximum and minimum temperatures, solar radiation and rainfall (amount and distribution parameters). Soil input files include such soil parameters as soil albedo, initial soil water content, soil textures, percent rocks and soil cation exchange capacity (CEC). The slope file includes the land physical features such as slope length, slope steepness and aspect. The management file provides plant and management information for different land uses (crop, range, or forest). For each land use, information about specific management practices are needed. For instance, for cropland, information about type of tillage, planting, harvesting, irrigation and date of each management practice is needed. The model simulates the effect of various management practices while simulating hydrological and erosion processes on the site.

For this validation exercise the WEPP input files were created based upon field observations. Rainfall, temperature, and radiation data were not available for the entire simulation years. Therefore, missing data were predicted using the WEPP climate generator component. Some of the soil and management parameters such as average ridge height, time of tillage, time of harvest, and surface roughness were not available, therefore, best appropriate values were used. For the period prior to the drainage installation, a WEPP model simulation without the subsurface drainage option was used. However, for the post-drainage period, a WEPP model simulation with the subsurface drainage option was used. Table 6.3.1 shows some of the important model parameters used in this validation test.

Table 6.1. Summary of WEPP parameters used for validation test of watershed.

average slope steepness	4 percent
slope length	250 m
soil texture	silt loam (21% sand, 56% silt, 23% clay)
crop	winter wheat
soil depth	1.51 m
depth to drain tiles	0.9 to 1.2 m *
drain tile diameter	0.1 m *
drain tile spacing	12 m *

* used in the subsurface drainage flow simulation

6.3.3 Results and Discussion

Comparison of daily measured and simulated storm runoff for the period prior to installation of drainage tiles is shown in Fig. 6.3.2 and 6.3.3. The data points are for periods (1-78 to 2-78 and 10-78 to 2-79) when rainfall and runoff were measured. The comparison was not made for days when runoff was significant but rainfall was reported as zero. Comparison of model simulated and measured peak runoff rates is provided in Fig. 6.3.3. The model-simulated storm runoff compares very well with the measured storm runoff, (r^2 = 0.92, Figure 6.3.2). However, the differences between model-simulated and measured peak runoff rate are somewhat greater (r^2 = 0.88, Fig. 6.3.3). Several reasons can be given for simulation errors in calculating peak runoff, including the fact that information about hydraulic roughness which depends on ridge heights and roughness, was not available and typical values were assumed.

Comparison of simulated and measured daily runoff for the period following installation of the subsurface drainage system is shown in Fig. 6.3.4. The data points are for the periods of 1-80 to 3-80 and 11-80 to 1-81 when rainfall and runoff were measured. Simulated and measured peak runoff rates are compared in Fig. 6.3.5. As was the case for the pre-drainage period, the results show that the model is capable of predicting total storm runoff. However, the differences between model simulated and measured peak runoff are less then acceptable (Fig. 6.3.5). For the data sets tested the model was conservatively-biased with consistent overprediction of peak runoff rates. The same argument that information about hydraulic roughness was not available and therefore model simulated peak runoff is an approximation is valid for this case. Unless information on hydraulic roughness is available, testing of the WEPP runoff routing component and, therefore, the validity of the model peak runoff calculations remain undetermined.

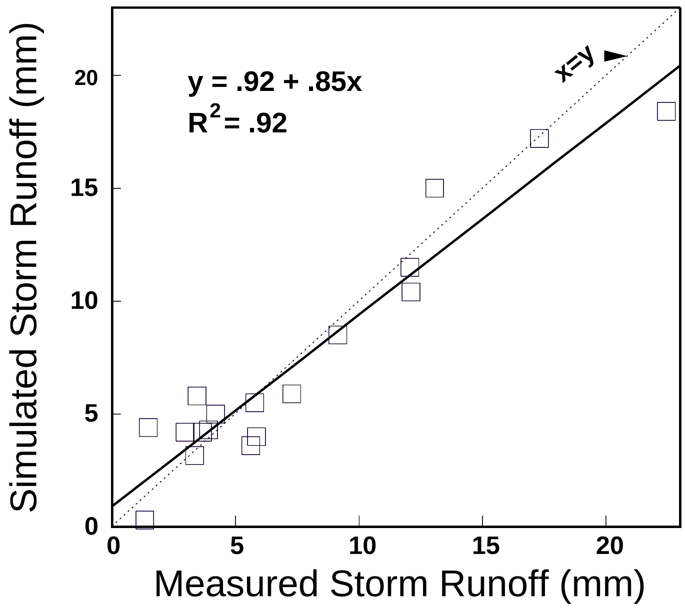

Figure 6.3.2. Comparison of model simulated and measured storm runoff for pre-drainage period.

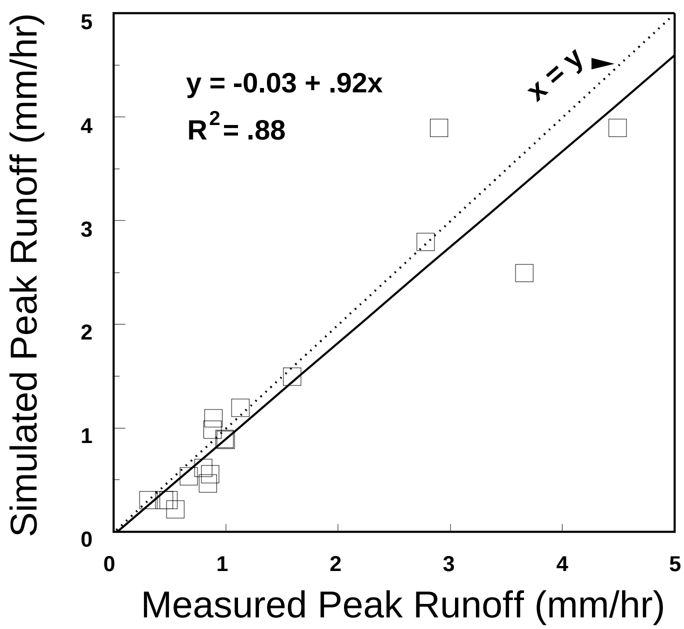

Figure 6.3.3. Comparison of model simulated and measured peak runoff for pre-drainage period.

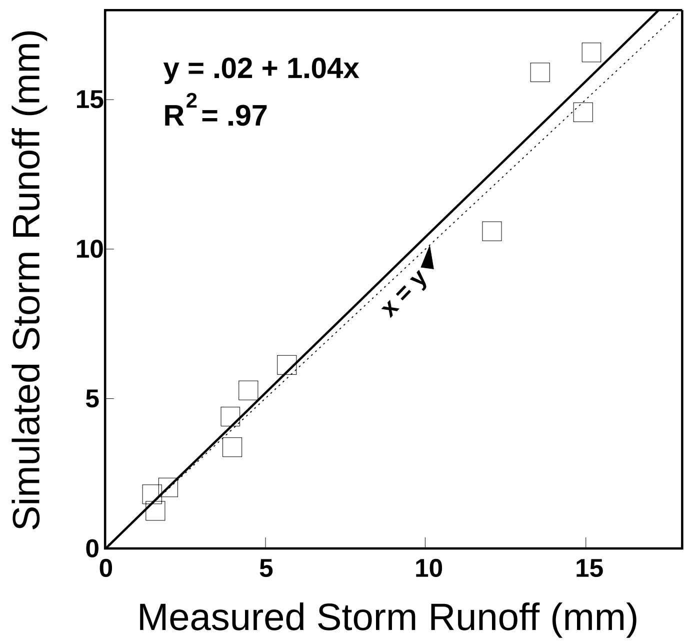

Figure 6.3.4. Comparison of model simulated and measured storm runoff after drainage installation period.

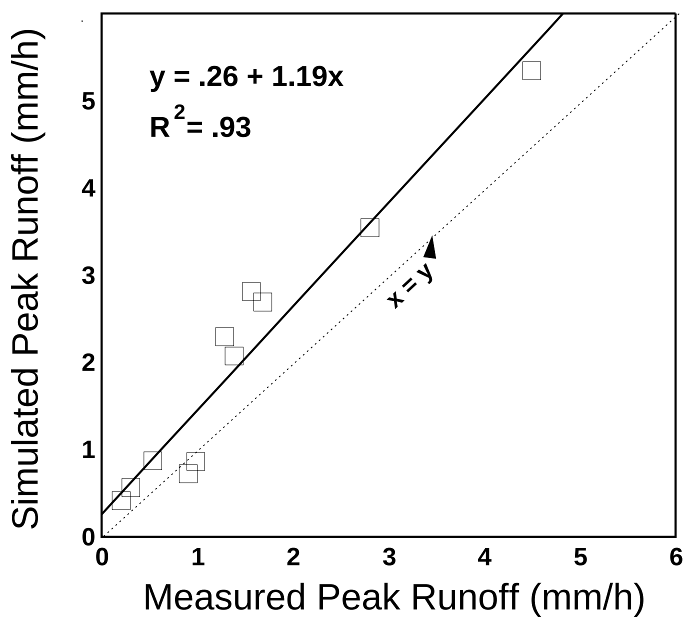

Figure 6.3.5. Comparison of model simulated and measured peak runoff after drainage installation period.

Close agreement between WEPP simulated and measured storm runoff for pre- and post-drainage treatments indicate that the model is capable of simulating the effect of subsurface drainage on storm runoff.

6.4 Summary

In WEPP, soil water content within each soil layer is subjected to percolation to lower layers, subsurface lateral flow, evapotranspiration, and flow to drainage tiles or ditches (if present). Soil water content of the uppermost soil layers (tillage layers, 0 - 20 cm depth) is used for infiltration calculation.

The ability of the model to predict storm runoff and peak runoff from a poorly drained watershed before and after subsurface drainage installation was evaluated. Although the WEPP model is not as sophisticated as other drainage models such as DRAINMOD and SWATREN (Dierickx et al., 1986) in calculating drainage flux and drain volume-water table depth relationship, close agreement between simulated and measured runoff in a validation trial on a watershed in Oregon indicates that the WEPP model is able to simulate the effect of subsurface drainage on storm runoff.

6.5 References

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6.6 List of Symbols

Symbol	Definition	Units
α	average slope angle of the flow path	rad
d	day of simulation	d
D_{dd}	daily subsurface drainage flux	$cm \cdot d^{-1}$
DS	depression storage	cm
ET	actual evapotranspiration from the drainable layer	$cm \cdot d^{-1}$
FL	accumulated amount of excess rainfall filling the depression storage	cm
g_e	effective porosity of 0-20 cm of soil	$cm^3 \cdot cm^{-3}$
h	distance between restrictive layer and drain tiles or the bottom of drain ditch	cm
h_e	equivalent depth	cm
h_i	soil water content of layer i	cm
H_o	drainable thickness	m
K_e	effective horizontal hydraulic conductivity	$cm \cdot d^{-1}$
K_z	horizontal hydraulic conductivity in saturated zone	$cm \cdot d^{-1}$
K_y	vertical hydraulic conductivity in saturated zone	$cm \cdot d^{-1}$
K_{zy}	effective hydraulic conductivity for subsurface drainage	$cm \cdot d^{-1}$
L	length of the hillslope	m
L_d	distance between drain tiles or ditches	cm
M_d	midpoint water table height above drain tiles	cm
PR	rainfall excess required to completely satisfy the hillslope storage	cm
Q	runoff rate leaving the profile	$cm \cdot h^{-1}$
Q_{dd}	drainage flux per unit width	$cm \cdot d^{-1}$
r	drain tube radius	cm
R_r	random roughness	cm
RO_d	daily surface runoff	cm
S	drainable depth of water	m
S_p	average slope steepness of an OFE	%
V	excess rainfall rate	$cm \cdot h^{-1}$
ϕ_D	drainable porosity	$cm^3 \cdot cm^{-3}$
ϕ	soil porosity	$cm^3 \cdot cm^{-3}$
θ	total soil moisture	$cm^3 \cdot cm^{-3}$
θ_a	entrapped air volume fraction	$cm^3 \cdot cm^{-3}$
θ_d	drainable soil water	$cm^3 \cdot cm^{-3}$
θ_{FC}	volumetric water content at field capacity	$cm^3 \cdot cm^{-3}$